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FINAL REPORT
FURTHER STUDY OF INVERSION LAYER
MIS SOLAR CELLS

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Prepared by
Fat Duen Ho
Fat Duen Ho, Principal Investigator
Professor, Electrical and
Computer Engineering
The University of Alabama in Huntsville
Huntsville, Alabama 35899
(205) 895-6168

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ABSTRACT

Many inversion layer Metal-Insulator-Semiconductor (IL/MIS) solar cells have been fabricated. As of today, the best cell fabricated by us has 9.138% AMO efficiency, with $FF = 0.641$, $V_{oc} = 0.557V$ and $I_{sc} = 26.90 \text{ mA}$. Efforts made for fabricating an IL/MOS solar cell with reasonable efficiencies are reported. The more accurate control of the thickness of the thin layer of oxide between aluminum and silicon of the MIS contacts has been achieved by using two different process methods. Comparison of these two different thin oxide processings is reported. The effects of annealing time of the sample are discussed. The range of the resistivities of the substrates used in the IL cell fabrication is experimentally estimated. Theoretical study of the MIS contacts under dark conditions is addressed.

1.0 INTRODUCTION

The objectives of this study are: (1) fabrication of 1cm^2 inversion-layer metal-insulator-semiconductor solar cells with good efficiencies; and (2) development of a simple, inexpensive process for fabricating high-efficiency IL solar cells.

Many inversion layer MIS solar cells have been fabricated since 1987. Most of them have low efficiencies, small short circuit currents, and small values of fill factors. There were only four quite satisfactory runs before 1990.

Close to the end of 1989, the furnaces in the B Wing of 4487 Building at Marshall Space Flight Center were dismantled. Our project was interrupted until July 1991.

Efforts have been made to control more accurately the thickness of the thin layer of oxide between aluminum and silicon of the MIS contacts. Using the furnace at 450°C , an oxide layer about 25 \AA can be grown on a $\langle 111 \rangle$ p-type silicon wafer in twenty minutes. The other successful method is to grow the thin oxide in a mixture of oxygen and nitrogen. These two processes have improved the open-circuit voltage, the short-circuit currents of the IL cells substantially. In the area of thermal oxidation, we changed the furnace temperatures for growing field oxide to see dependence of fixed oxide charge for $\langle 111 \rangle$ silicon on final oxidation temperature.

Besides experimental work done in the Micro-electronics Laboratory at MSFC, with Mr. P. D. MacManus, we have also done some theoretical work on MIS contacts under dark conditions, which is an effort of Dr. Ho and his graduate student, Mr. Doghish, at the University of Alabama in Huntsville. It has been discussed in some detail in this report.

2.0 BACKGROUND AND OVERVIEW

The operational principle and the design consideration of inversion-layer metal-insulator-semiconductor (IL/MIS) solar cells have been discussed in some detail in other papers [1] - [8]. Here, only a brief review is given.

The advantages of IL/MIS solar cells are that the processing is mainly at low temperature and the diffusion-induced crystal damage of diffused p-n junction cells does not exist. There is no "dead layer" in these cells. Therefore, their responses to ultraviolet light are better than those of diffused p-n junction solar cell. The IL/MIS cells may have nearly ideal diode properties. As a result, they can have a larger value of open-circuit voltage.

In order to have the highest possible efficiency, we must optimize the structure of inversion-layer MIS cells. The most important parameters of the inversion-layer cells, for design consideration, are: (1) the resistivity of the substrate; (2) the fixed charge in the oxide or other insulators; (3) the number of grids per unit length; and (4) the thickness of the interfacial layer of the thin oxide in an MIS contact.

The substrate of an inversion-layer MIS cell must be p-type with the $\langle 111 \rangle$ orientation. It should not be doped too heavily or too lightly. The heavily doped substrates may have difficulty in inverting the thin inversion layer beneath the insulator (oxide, nitride, etc.) The lightly doped substrates may have too large sheet resistance of the inversion layer. Increasing the number of grid lines can reduce the sheet resistance of the inversion layer, but too many grid lines would reduce the cell area exposed to the sunlight. These two parameters have their opposite effects, which should be compromised to get an optimized result.

3.0 GROWTH OF THIN OXIDE IN AN MIS CONTACT

In the study of the inversion-layer cells, metal-insulator-semiconductor rectifying contacts have received much attention. These efforts result in a better understanding of the carrier flow across the barrier. It is found that the parameters of the MIS contacts govern the carrier flow across the barrier are the insulator, the work function of the selected metal, and the interface traps.

The thickness of the thin oxide in the MIS contact plays a very critical role in fabricating the inversion-layer MIS solar cells. The oxide must be thin enough to guarantee that the tunneling effect is enough. However, if the interfacial layer is too thin, the open-circuit voltage will be too low. Therefore, the thickness of the insulating thin oxide should be optimized.

Controlling the thin layer of oxide in an MIS contact more accurately has been a very important task in our project. We used two different methods to grow thin oxide. Using the furnace with 450° C, an oxide layer about 25Å can be grown in a pure oxygen on a <111> p-type silicon wafer in about twenty minutes. The other method is to grow thin oxide in a mixture of O₂ and N₂. Both methods of producing thin oxide gave good results.

4.0 THE FABRICATION PROCEDURES FOR IL/MIS SOLAR CELLS

The fabrication procedures of the IL solar cells are summarized as follows:

- (1) Field oxide with a thickness of approximately 1400Å is thermally grown on p-type silicon substrate with <111> orientation;
- (2) Metal contact regions are defined, using the first mask;
- (3) Thin oxide is grown in metal contact regions;
- (4) The back surface of the sample is metallized;

- (5) Back metal is sintered in 470°C furnace;
- (6) Aluminum is evaporated for front metallization;
- (7) Grid patterns of the front metal are defined, using a second mask.

5.0 THEORETICAL STUDY OF MIS CONTACTS

We have been developing a comprehensive model for MIS (Metal-Oxide-Semiconductor) contacts under dark conditions, which consists of a wide range of parameters. The effects of surface states, silicon dioxide thickness, substrate doping, fixed oxide charges, substrate thickness, and metal work function are all taken into account.

The effects of changing the values of parameters on the behavior of the MIS contacts are summarized as follows:

(1) Effects of changing Φ_m

The different values of work functions of metals, Φ_m , affect the current-voltage characteristics of MIS contact under dark conditions. for Φ_m less than some value (Φ_{mc}) the I-V characteristic can be represented by an equation similar to that of a simple conventional diode equation.

When increasing $\Phi_m > \Phi_{mc}$, a simple diode equation is no longer valid to describe the I-V characteristic. It becomes more complicated. For $\Phi_m < \Phi_{mc}$, the semiconductor is strongly inverted. For $\Phi_m > \Phi_{mc}$, it is not strongly inverted, and the semiconductor charges Q_{sc} are mainly the depletion layer charges.

For $\Phi_m < \Phi_{mc}$, the split between the electron and hole Fermi levels Φ_s is approximately equal to the applied voltage, especially for reverse bias. The dominant component of current is the diffusion current, J_{Dn} , for reverse bias, and for small forward bias. The MIS contact is now in near equilibrium conditions, and the total current is small. For higher forward applied voltage, the near equilibrium conditions are not satisfied, and the split between the electron and hole Fermi levels Φ_s becomes less than the applied voltage. The device is driven to depletion, and the current becomes larger. the main component of current is now due to the recombination in the depletion region (J_{rg}). The hole and electron tunneling currents (J_{pt} , J_{nt}) through the thin oxide are negligibly small. The simple theory of diode, represented by Eq. (1) can be applied.

$$J = J_0 \left(e^{\frac{v}{nV_t}} - 1 \right) \quad (1)$$

where n is the ideality factor, which now depends on the relative value of J_{rg} .

For $\Phi_m > \Phi_{mc}$, the MIS contact is no longer at strong inversion, except for very high reverse bias. The dominant component of dark current is now that passes through the surface state J_{ps} . The diffusion current (J_{dn}) and the recombination current in depletion region (J_{rg}) becomes less important and can be neglected.

The device is now under non-equilibrium conditions. The tunneling through surface states dominates and controls the behavior of the MIS

contact. The dark current J_{dark} is approximately equal to J_{ps} (the dark current which passes through the surface states) which has a complicated relation with V .

The I-V characteristics of a MIS contact for different metal work function Φ_m is shown in Fig. 1. The surface potential Ψ_s of a MIS contact for different metal work function Φ_m is shown in Fig. 2. The split of Fermi levels Φ_s of a MIS contact for different metal work function Φ_m is shown in Fig. 3.

(2) Effects of Changing N_a

The doping concentrations of the silicon substrate affect the dark current of the MIS contact. There is a critical value N_{ac} , under which the I-V characteristic follows the ideal diode equation (Eq. [1]). This N_{ac} is found to be around 10^{17}cm^{-3} .

For $N_a < N_{ac}$, the split between the two Fermi levels of electrons and holes (Φ_s) varies with the applied voltage, and the increment of the surface potential is the same as that of the applied voltage, V . This means that the system is in near equilibrium conditions. The main components of dark current are the diffusion current J_{dn} for reverse and small forward bias, and the recombination current in depletion region J_{rg} for reverse bias. The main tunneling current is due to the minority carriers. Therefore, this device for $N_a < N_{ac}$ is called minority carrier device.

For $N_a > N_{ac}$ the system is at non equilibrium, and the split Φ_s does not

follow the applied voltage. The split Φ_s is approximately zero for reverse biases, and has a low value for forward biases. The surface potential is approximately constant, and most of the applied voltage exists as a voltage drop across the oxide. The semiconductor surface can not reach inversion conditions. It is always in depletion, with a higher concentration of holes and lower concentration of electrons. The tunneling through the oxide occurs mainly by holes. As a result, the device is a majority carrier device with J_{pt} (the hole tunneling current) dominates at reverse bias, and J_{ps} and J_{pt} dominate at forward bias.

The I-V characteristics of a MIS contact for different doping density N_a is shown in Fig. 4.

(3) Effects of the thickness of the thin oxide layer

The oxide thickness, d_i , is an important parameter which affects the I-V characteristics of MIS contacts. Its effect depends on the choice of the other parameters. If the other parameters are chosen such that the device becomes minority carrier device. In this case, for lower d_i the applied voltage drop (V) is mainly across the semiconductor and the split between the two fermi levels (ϕ_s) is equal to V , and the surface potential (ψ_s) follows V . the main components of current are J_{rg} (for reverse bias and small forward bias.) and J_{Dn} (for large forward bias). The hole tunneling current J_{pt} is high, but less than J_{Dn} .

As the oxide thickness (d_i) is increased, the tunneling current (J_{pt})

drops sharply. The band bending (ψ_s) does not follow V and Φ_s becomes less than V , and the system becomes far from equilibrium. The voltage drop across the insulator increases. The surface states have greater effect on the I-V characteristics until J_{pt} dominates for higher forward bias.

The I-V characteristics of a MIS contact for different oxide thickness (di) for constant surface states D_{it} and for metal work function $\Phi_m = 4.1\text{eV}$ is shown in Fig. 5.

6.0 RESULTS AND DISCUSSION

Many inversion layer MOS solar cells have been fabricated in this period of time of research on the IL/MOS solar cells. Most of them have low efficiencies, small short circuit currents, and small values of fill factors. There were only four quite satisfactory runs before 1990.

The best IL/MIS cell has 9.138% AMO efficiency with $FF = 0.641$, $V_{oc} = 0.557\text{V}$ and $I_{sc} = 26.90\text{ mA}$, which is shown in Figure 6. The second best cell has 8.77% AMO efficiency with $FF = 0.524$, $V_{oc} = 0.57\text{V}$ and $I_{sc} = 30.5\text{ mA}$, which is shown in Figure 7. The third best cell has 8.51 % AMO efficiency, with $FF = 0.63$, $V_{oc} = 0.549\text{V}$ and $I_{sc} = 25.85\text{ mA}$, which is shown in Figure 8. Close to the end of 1989, the furnaces in the B Wing of 4487 Building at MSFC were dismantled. Our project had been interrupted until July 1991.

In the Clean Room in the C Wing of 4487 Building, there were two runs in July and August of 1991. The best IL/MIS cell has 4.782 % AMO efficiency, with $FF = 0.399$, $V_{oc} = 0.496$, and $I_{sc} = 25.40\text{ mA}$.

There are two methods to grow thin oxide in the IL/MIS device. One is to grow it

in pure oxygen. The other one is to grow it in a mixture of oxygen and nitrogen. The comparison of these two methods is shown in Table 1. We do not have enough data to draw a conclusion for using these two different methods. Generally speaking, both processing methods gave good results. Using the mixture of O_2 and N_2 is better when the furnaces for growing thin oxide have moisture problems.

The effect of changing annealing time for the performance of the solar cells is demonstrated in Table 2. It shows that twenty minutes is needed to anneal the sample to produce better results of I_{sc} , V_{oc} , and the cell efficiency.

The experimental results of the IL/MIS solar cells using different resistivities of the substrates have been listed in Table 3 for comparison. It shows that the substrates with resistivities ranging from $0.7 \Omega\text{-cm}$ to $6\Omega\text{-cm}$ made better IL/MIS cells. When the substrate resistivities are too low, such as $0.012\Omega\text{-cm}$ and $0.005 \Omega\text{-cm}$, the IL/MIS solar cells have very low values of V_{oc} , I_{sc} and efficiencies.

7.0 REFERENCES

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TABLE 1

Comparison of experimental results of the IL/MIS solar cells in Run # SCHO 13/89, using different methods for growing thin oxide (Number of metal lines = $49\frac{3}{4}\text{ cm}^{-1}$; Total area = 0.907 cm^2 ; Active area = 0.777 cm^2 ; Substrate thickness = 0.0381 cm).

Wafer Sample		Thin Oxide Grown in	Resistivity of Substrates	FF	I_{sc} (mA)	V_{oc} (V)	Efficiency
13-1	A	O ₂ only	1.3 Ω -cm	0.553	27.15	0.563	8.046%
	B	O ₂ only	1.3 Ω -cm	0.561	27.4	0.567	8.285%
	C	O ₂ only	1.3 Ω -cm	0.430	25.85	0.559	5.914%
	D	O ₂ only	1.3 Ω -cm	0.437	25.9	0.561	6.037%
	A	Mixture, O ₂ & N ₂	1.3 Ω -cm	0.594	26.25	0.552	8.187%
	B	Mixture, O ₂ & N ₂	1.3 Ω -cm	0.596	26.00	0.555	8.178%
	C	Mixture, O ₂ & N ₂	1.3 Ω -cm	0.630	25.85	0.549	8.510%
	D	Mixture, O ₂ & N ₂	1.3 Ω -cm	0.641	26.90	0.557	9.136%

TABLE 2

Comparison of experimental results of the IL/MIS solar cells in Run # SCHO 2/90, using different annealing time (Number of metal lines = $49 \frac{3}{4} \text{ cm}^{-1}$; Total area = 0.907 cm^2 ; Active area = 0.777 cm^2 ; Substrate thickness = 0.0381 cm , Resistivity = $1.3 \Omega \cdot \text{cm}$).

Wafer Sample		Thin Oxide Grown in	Annealing time	FF	I_{sc} (mA)	V_{oc} (V)	Efficiency
2-1	A	Mixture, O_2 & N_2	5'	0.541	24.8	0.522	6.663%
	B	Mixture, O_2 & N_2	5'	0.417	24.75	0.504	4.944%
	C	Mixture, O_2 & N_2	5'	0.542	24.95	0.529	6.809%
	D	Mixture, O_2 & N_2	5'	0.378	24.9	0.509	4.552%
2-2	A	Mixture, O_2 & N_2	20'	0.570	23.6	0.554	7.086%
	B	Mixture, O_2 & N_2	20'	0.502	25.75	0.553	6.797%
	C	Mixture, O_2 & N_2	20'	0.603	25.70	0.547	8.067%
	D	Mixture, O_2 & N_2	20'	0.579	25.05	0.540	7.453%

TABLE 3

Comparison of experimental results of the IL/MIS solar cells in Run # SCHO 14/89, using different values of Resistivity of the Substrates (Number of metal lines = $49 \frac{3}{4} \text{ cm}^{-1}$; Total area = 0.907 cm^2 ; Active area = 0.777 cm^2 ; Substrate thickness = 0.0381 cm .)

Wafer Sample		Thin Oxide Grown in	Resistivity of Substrates	FF	I_{sc} (mA)	V_{oc} (V)	Efficiency
14-2	A	Mixture, O_2 & N_2	$0.7\text{-}1.3 \Omega\text{-cm}$	0.572	24.7	0.546	7.335%
	B	Mixture, O_2 & N_2	$0.7\text{-}1.3 \Omega\text{-cm}$	0.576	24.45	0.546	7.308%
	C	Mixture, O_2 & N_2	$0.7\text{-}1.3 \Omega\text{-cm}$	0.564	24.55	0.54	7.117%
	D	Mixture, O_2 & N_2	$0.7\text{-}1.3 \Omega\text{-cm}$	0.568	24.85	0.54	7.345%
14-3	A	Mixture, O_2 & N_2	$3\text{-}6 \Omega\text{-cm}$	0.589	25.9	0.557	7.643%
	B	Mixture, O_2 & N_2	$3\text{-}6 \Omega\text{-cm}$	0.569	25.75	0.525	7.322%
	C	Mixture, O_2 & N_2	$3\text{-}6 \Omega\text{-cm}$	0.590	25.6	0.528	7.586%
	D	Mixture, O_2 & N_2	$3\text{-}6 \Omega\text{-cm}$	0.557	25.75	0.528	7.147%
14-4	A	Mixture, O_2 & N_2	$0.2\text{-}0.5 \Omega\text{-cm}$	0.560	22.7	0.559	6.763%
	B	Mixture, O_2 & N_2	$0.2\text{-}0.5 \Omega\text{-cm}$	0.574	22.3	0.568	6.915%
	C	Mixture, O_2 & N_2	$0.2\text{-}0.5 \Omega\text{-cm}$	0.476	18.25	0.507	4.194%
	D	Mixture, O_2 & N_2	$0.2\text{-}0.5 \Omega\text{-cm}$	0.508	19.5	0.524	4.939%
14-5	A	Mixture, O_2 & N_2	$8\text{-}12 \Omega\text{-cm}$	0.441	26.75	0.503	5.642%
	B	Mixture, O_2 & N_2	$8\text{-}12 \Omega\text{-cm}$	0.488	25.60	0.501	5.957%
	C	Mixture, O_2 & N_2	$8\text{-}12 \Omega\text{-cm}$	0.444	27.35	0.504	5.817%
	D	Mixture, O_2 & N_2	$8\text{-}12 \Omega\text{-cm}$	0.498	26.95	0.508	6.490%
14-1		Mixture, O_2 & N_2	$0.005 \Omega\text{-cm}$	***	***	***	***
14-6		Mixture, O_2 & N_2	$0.012 \Omega\text{-cm}$	***	***	***	***

*** NOT MEASURABLE

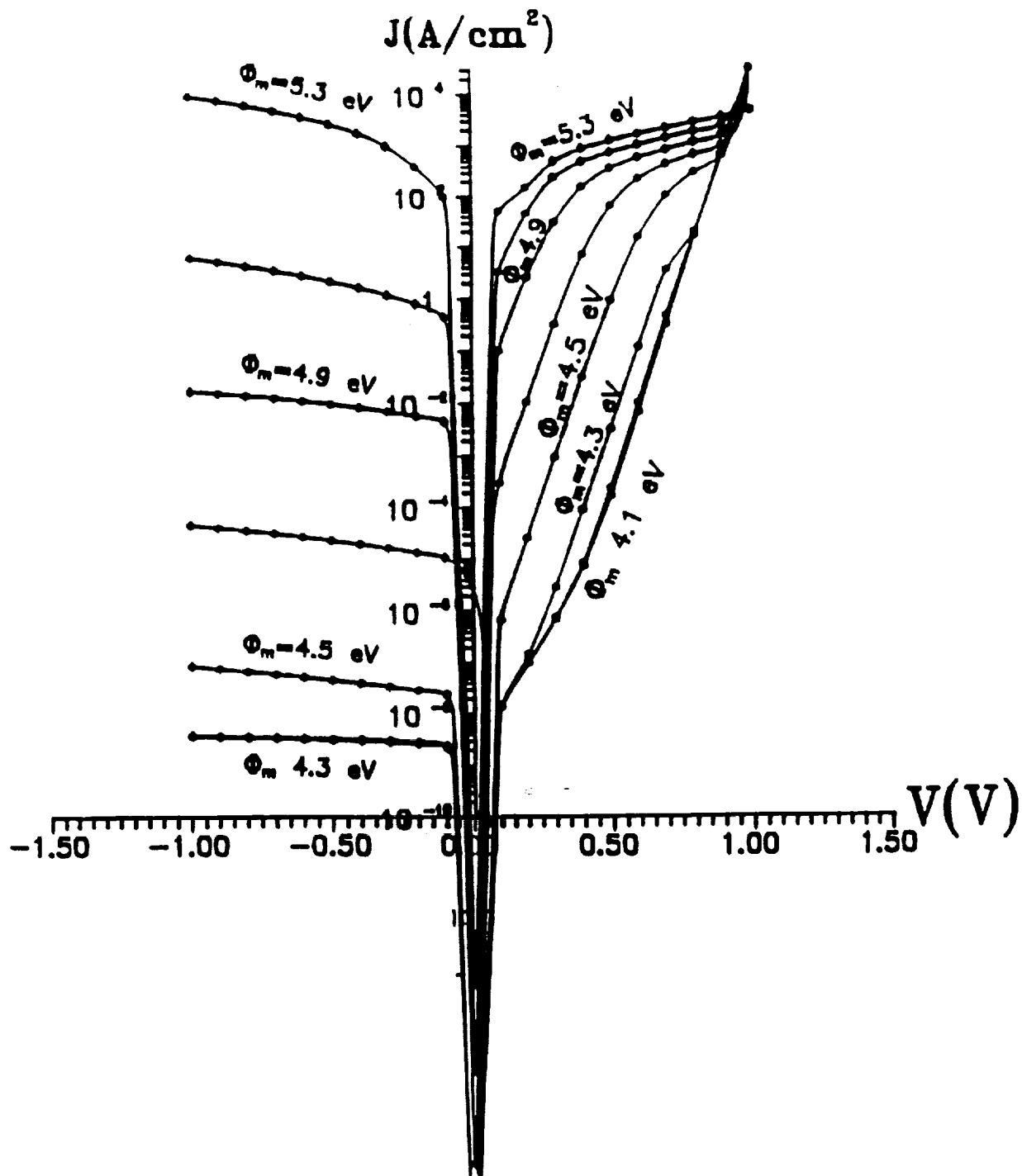


Figure 1: The I - V characteristics of a MIS contact for different metal work functions $\phi_M(\text{eV})$

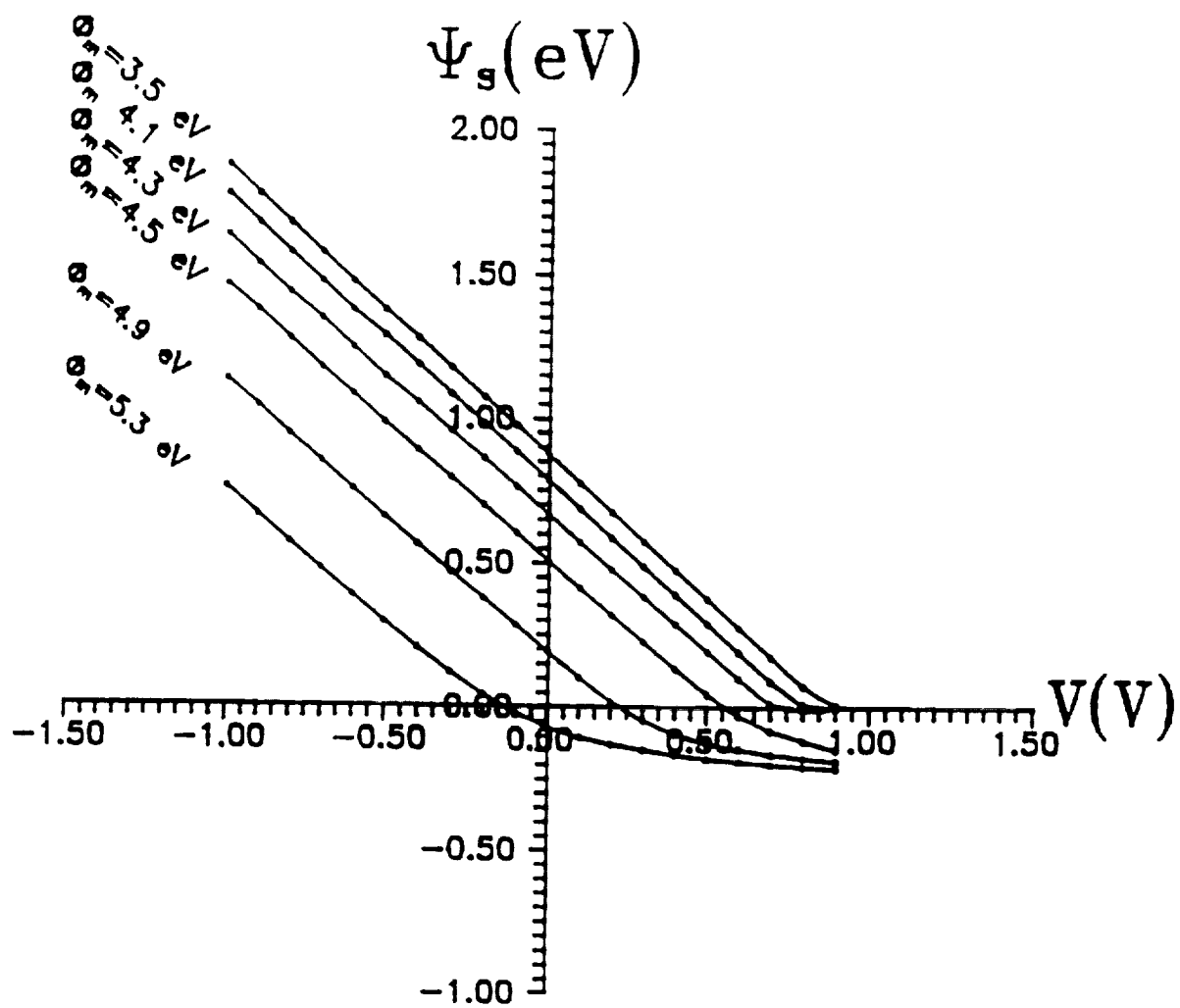


Figure 2: The surface potential Ψ_s of a MIS contact for different metal work functions Φ_m (eV).

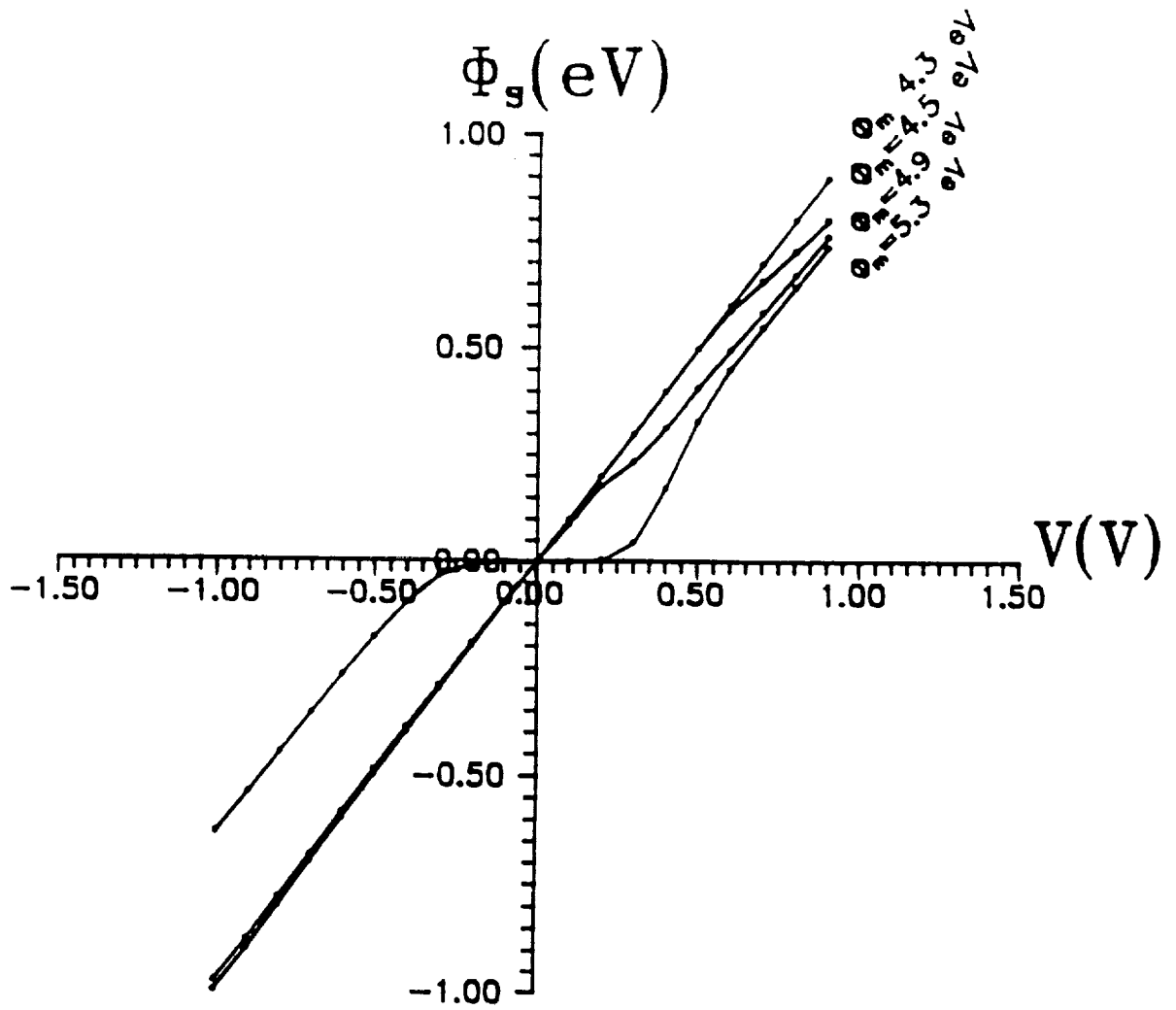


Figure 3: The split of Fermi levels Φ_s of a MIS contact for different metal work functions Φ_m (eV).

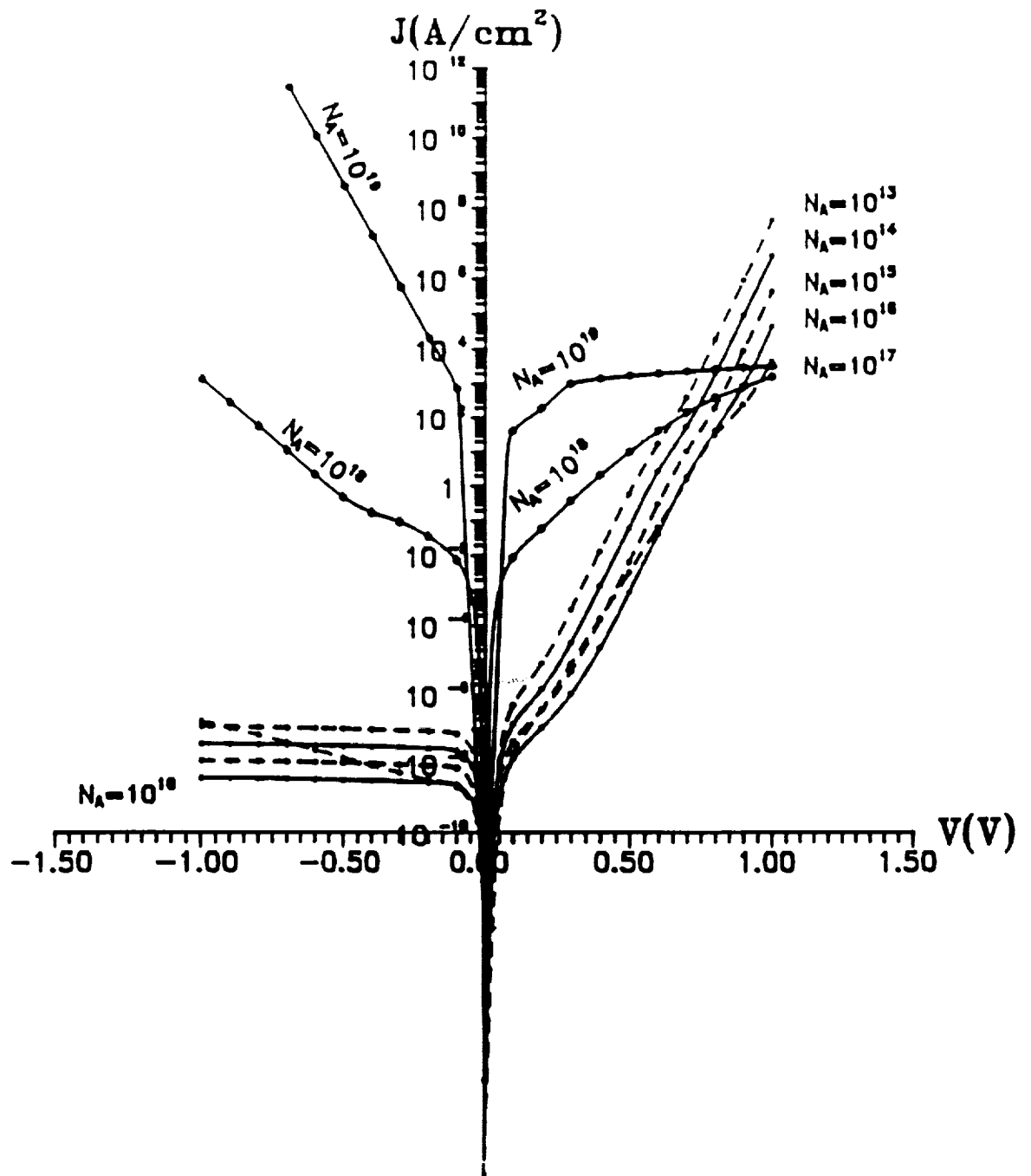


Figure 4: The I-V characteristics of a MIS contact for different doping densities N_A (cm^{-3}).

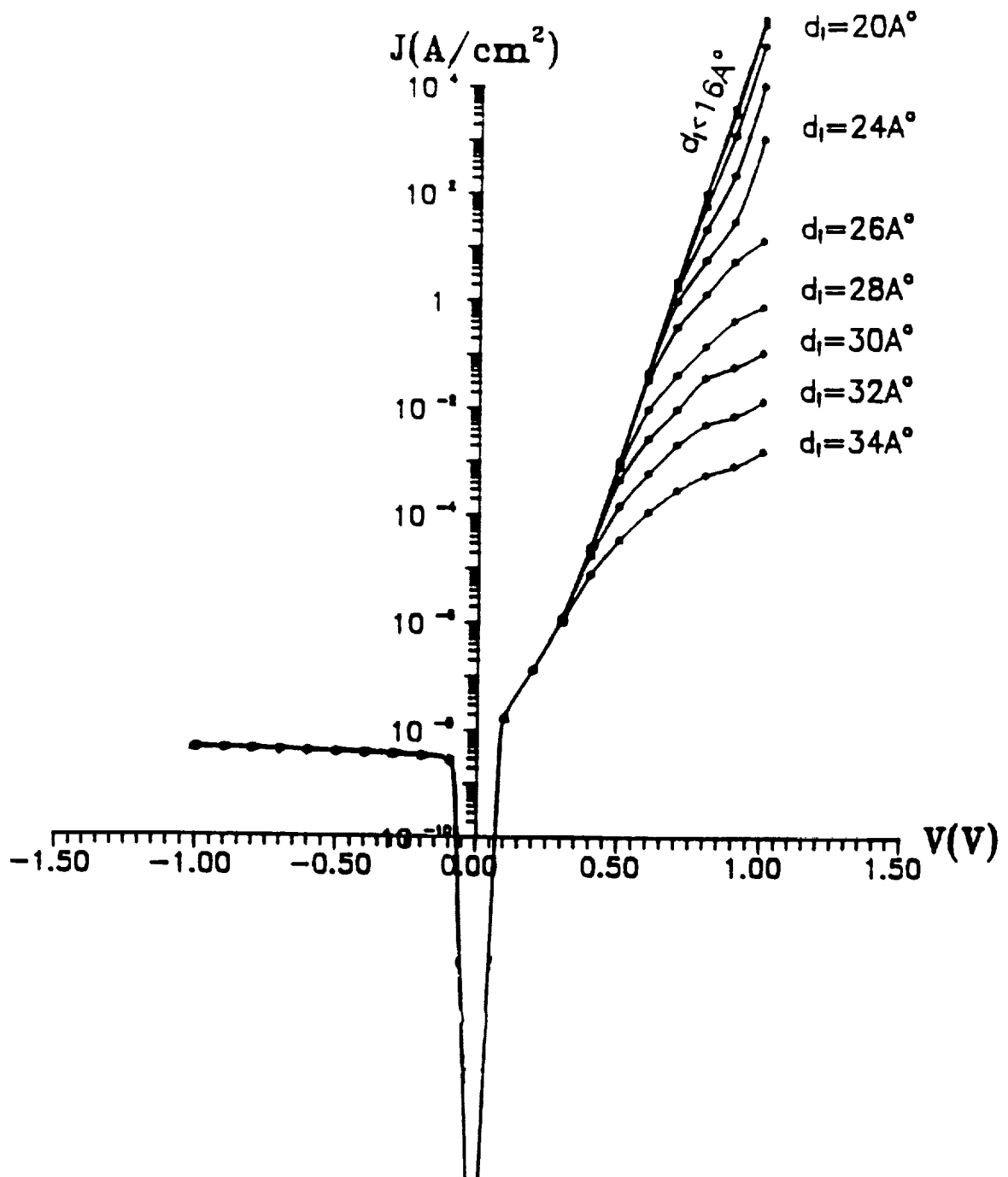
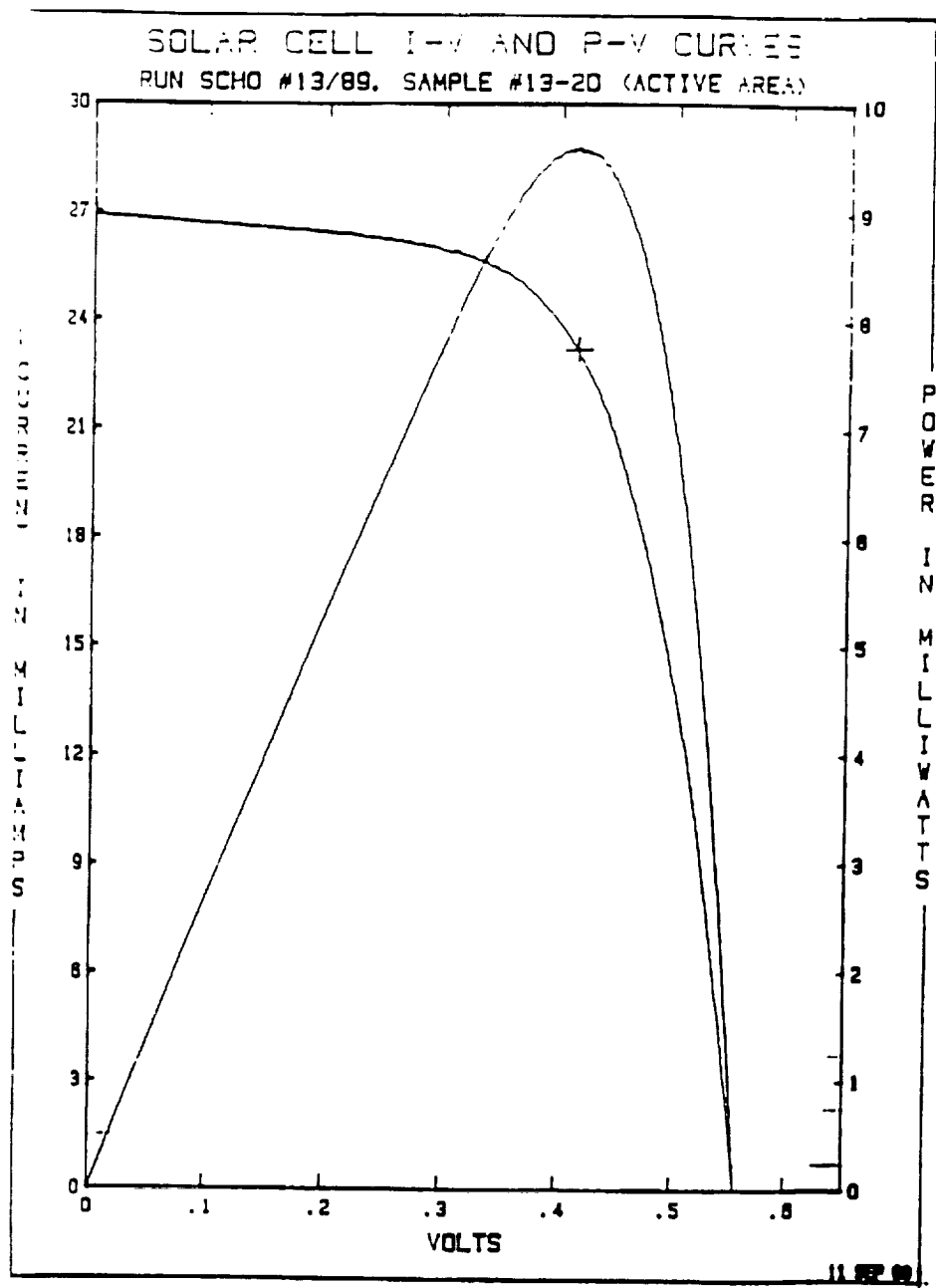


Figure 5: The I-V characteristics of a MIS contact for different oxide thicknesses (d_1) for constant surface states D_{it} and for metal work function $\Phi_M = 4.1$ eV.

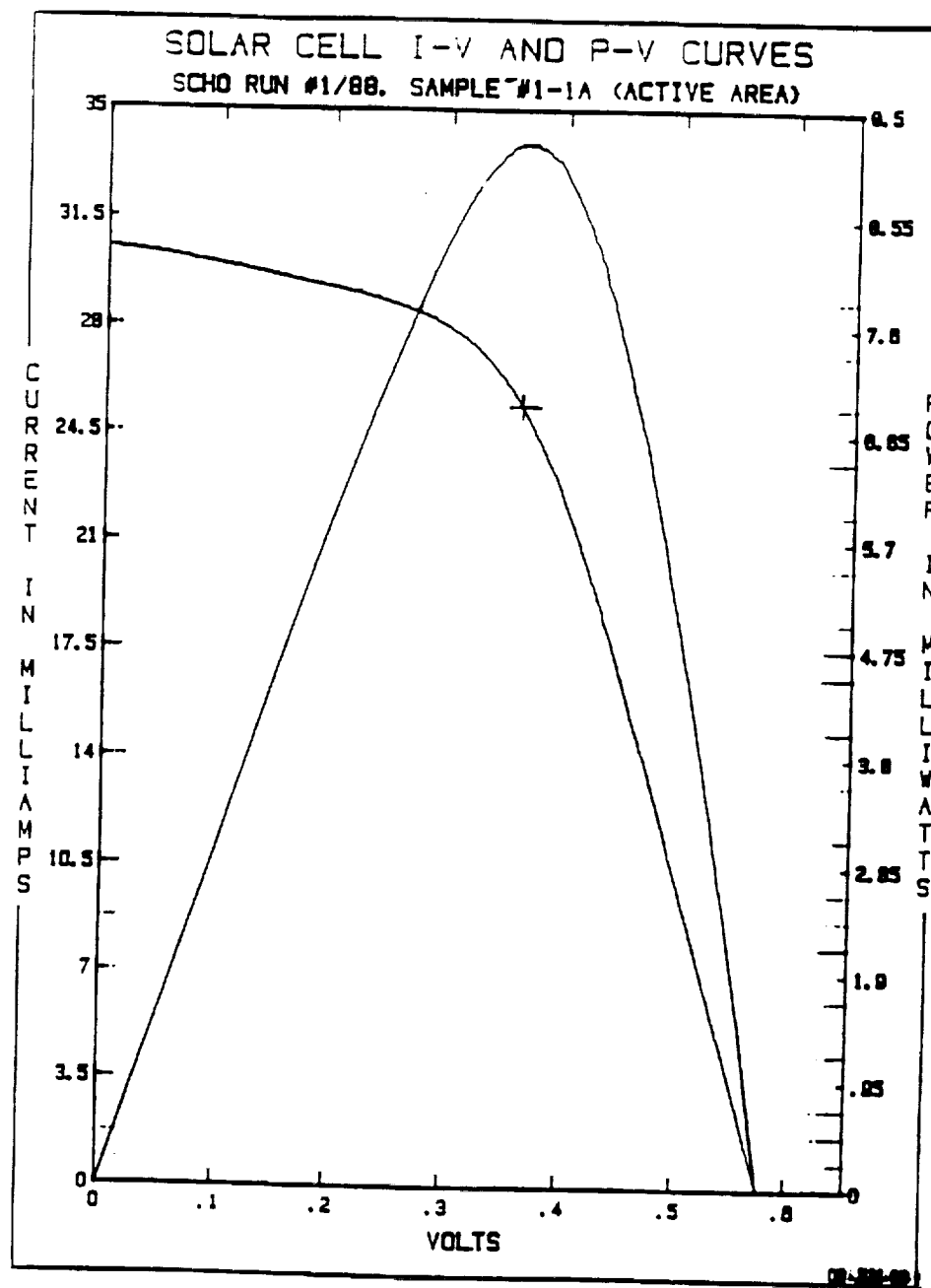


VM = .414 V
IM = 23.2 mA

VOC = .557 V
ISC = 26.9 mA

Efficiency = 9.136%
FF = .641

Figure 6: Solar cell I-V and P-V curves, Sample #13-20.

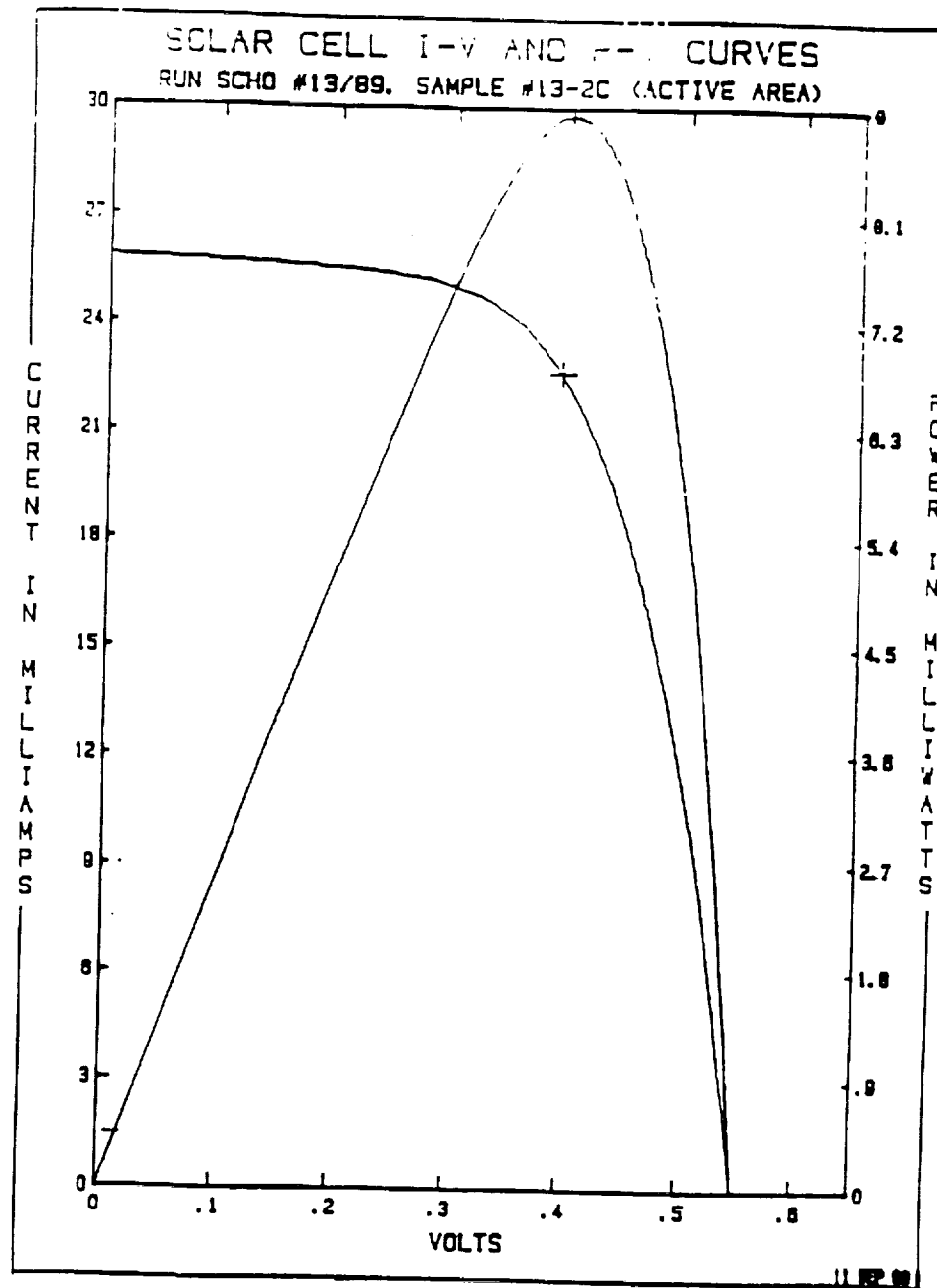


VM = .383 V
IM = 25.4 mA

VOC = .557 V
ISC = 30.5 mA

Efficiency = 8.77%
FF = .524

Figure 7: Solar cell I-V and P-V curves, Sample #1-1A.



VM = .395 V
 IM = 22.65 mA

VOC = .5495 V
 ISC = 25.85 mA

Efficiency = 8.51%
 FF = .63

Figure 8: Solar cell I-V and P-V curves, Sample #13-2C.